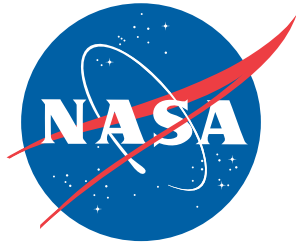


NASA/TM-2012-217599
NESC-RP-12-00779



Space Shuttle Program (SSP) Shock Test and Specification Experience for Reusable Flight Hardware Equipment

*Curtis E. Larsen/NESC
Langley Research Center, Hampton, Virginia*

August 2012

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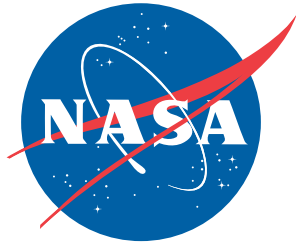
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National Aeronautics and
Space Administration

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April 26, 2012

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Approved:	<i>Original Signature on File</i>	5/1/12
	NESC Director	Date

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1.0	Initial Release	Dr. Curtis E. Larsen, NASA Technical Fellow for Loads and Dynamics, JSC	4/26/12

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1.0 Signature Page

Submitted by:

Team Signature Page on File – 5/2/2012

Dr. Curtis E. Larsen Date

Prepared by:

Mr. Robin C. Ferebee Date

Signatories declare the findings, observations, and NESC recommendations compiled in the report are factually based from data extracted from Program/Project documents, contractor reports, and open literature, and/or generated from independently conducted tests, analyses, and inspections.

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2.0 Team List

Name	Discipline	Organization/Location
Core Team		
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Saverio D'Agostino	Materials	JPL
Robin Ferebee	Loads and Dynamics	MSFC/KSC Resident Office
Vincent Fogt	Loads and Dynamics	JSC
Tom Irvine	Loads and Dynamics	DCI, Huntsville
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Daniel Kaufman	Loads and Dynamics	GSFC
Rhonda Smith	Deputy Manager, MTSO	LaRC
Administrative Support		
Christina Williams	Technical Writer	LaRC/ATK

2.1 Acknowledgement

Mr. Robin Ferebee of the Marshall Space Flight Center (MSFC) Shuttle Propulsion Chief Engineer's Office, Kennedy Space Center (KSC) Resident Office, provided primary leadership for the completion of this task and authored this paper on the Space Shuttle Program (SSP) solid rocket booster (SRB) shock qualification experience.

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3.0 Executive Summary

As commercial companies are nearing a preliminary design review level of design maturity, several companies are identifying the process for qualifying their multi-use electrical and mechanical components for various shock environments, including pyrotechnic, mortar firing, and water impact. The experience in quantifying the environments consists primarily of recommendations from Military Standard (MIL-STD)-1540, *Product Verification Requirement for Launch, Upper Stage, and Space Vehicles*. Therefore, the NASA Engineering and Safety Center (NESC) formed a team of NASA shock experts to share the NASA experience with qualifying hardware for the Space Shuttle Program (SSP) and other applicable programs and projects. Several team teleconferences were held to discuss past experience and to share ideas of possible methods for qualifying components for multiple missions.

At one of the teleconferences, Mr. Robin Ferebee discussed how the Marshall Space Flight Center (MSFC) calculated shock criteria based on enveloping available data rather than calculating probability levels, and the analysts' latitude in selecting the level of conservatism that was used. Mr. Saverio D'Agostino explained that the Jet Propulsion Laboratory methodology is to generally use a 6-decibel (dB) margin to calculate their criteria. He described results from soil impact tests which, in some cases, led to extremely high shock levels.

Mr. Ferebee described several SSP solid rocket booster (SRB) rate gyro pivot failures from either pyrotechnic or water impact shock, although NASA was never able to determine the cause. Mr. Ferebee also described the Space Transportation System (STS)-4 failure when both SRBs were lost when the parachutes released prematurely due to a g-switch that falsely sensed water impact during the frustum deployment. The only other failure was a structural failure of an electronic box due to the water force from cavity collapse on the SRB motor case. No other reported failures were identified by the team. However, Mr. Tom Irvine of Dynamic Concepts Inc., identified a reference paper by Moening¹ on industry pyrotechnic shock failures.

Test methodology was also discussed during the teleconferences. Although the anvil test method can be used for convenience, achieving the required levels in the 100-Hz region can be difficult. Instead, the NESC team recommends shaker testing. Difficulties in achieving shaped spectra when using a pyrotechnic plate were also discussed. The SRB Project maintained the same spectrum shape even when calculations showed that it should have lower frequency content, knowing that in actual testing the hardware would likely be exposed to levels that would encompass the calculated levels.

Mr. Irvine described the idea of exposing test hardware to one shock at the qualification level of 6 dB above the maximum expected, and then the remaining shocks at the maximum expected. However, the NESC team had discussed this possibility of accelerated testing for shock and

¹Moening, C.J., "Pyrotechnic Shock Flight Failures," *IES Pyrotechnic Shock Tutorial Program*, 31st ATM, Institute of Environmental Sciences, April-May 1985.

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collectively recommended against it because there are no known material fatigue curves that would apply.

The importance of post-flight inspection and hardware recertification before re-flight was emphasized. Recertification includes hardware inspection followed by environmental acceptance and functional tests at the component and system levels. The SRB Project performs this activity on electrical and thrust vector control hardware through exposure to a system level hotfire to exercise the system.

In summary, the NESC recommends shock qualification for the expected number of reuses, and hardware recertification prior to each flight, including environmental acceptance tests and functional tests at the component and system level.

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4.0 SSP Experience Introduction

The SSP had many unique characteristics that were previously unexplored in other programs, one of which was reusability. The majority of the SSP stack, with the exception of the external tank (ET), was designed for reusability. The SRB structural elements were designed for 40 missions, and the electrical and mechanical components were designed for 20 missions. Predictions of the environments that the components would experience were based on previous vehicle history and sub-scale testing. The electrical and mechanical components were qualified for the appropriate predicted environments.

4.1 STS Mission Profile

Two SRBs provide about 83 percent of the thrust at liftoff and during the first stage ascent. They are jettisoned approximately 2 minutes after launch at a height of about 150,000 feet, and then parachutes are deployed and land in the ocean to be recovered. Figure 4.1-1 illustrates the complex re-entry and landing sequence. The major shock events during SRB flight are holddown bolt release, booster separation, frustum separation, parachute deployment, nozzle extension separation, and water impact. Water impact occurs at about 75 feet per second, although past impacts have been estimated as high as 110 feet per second due to parachute failures. The boosters are then towed back to Cape Canaveral Air Force Station to begin the refurbishment process.

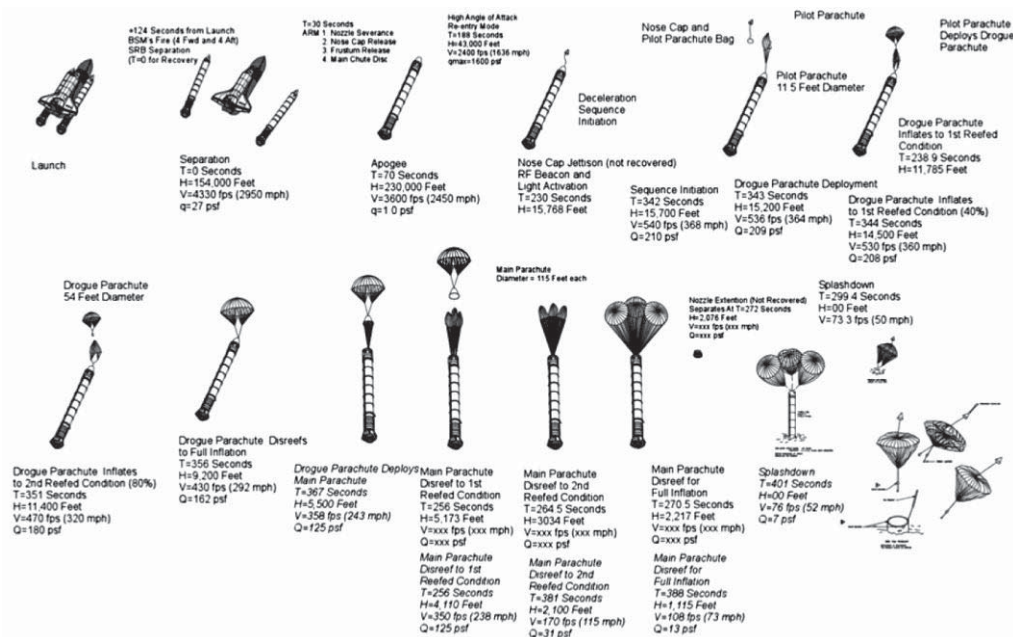


Figure 4.1-1. STS SRB Re-entry Sequence

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5.0 Environment Prediction and Test Criteria Derivation

Sub-scale testing using 6- and 12-inch diameter models was conducted to determine loading and acceleration of the SRB structure during water impact [ref. 1]. While the 12-inch model was constructed to simulate the dynamic effects of the structure, no effort was made to simulate the equipment mounting structure (e.g., ring frames and equipment panels). Consequently, the rigid body and low frequency dynamic effects were included in the initial environments, but not the response of the secondary structures.

Pyrotechnic shock environments were calculated using the shock database produced by the Goddard Space Flight Center and the Martin-Marietta Corporation [ref. 2]. Hundreds of measurements on various launch vehicles were compiled into this database and crude scaling techniques were used to account for shock dissipation through the structures and for attenuation through joints.

Qualification criteria were based on maximum expected environments with no added margin, based on a 97.5 percent probability level. There was no benefit to adding margin above maximum expected because the predicted levels appeared sufficiently conservative based on the available database and associated assumptions. Since there was a relatively limited amount of shock data, all of the applicable data was enveloped rather than using a probability level. One shock per mission was specified, depending on the test method. For testing performed on a shaker table, one shock per axis per mission was required. For pyrotechnic plates, one shock per mission was required and at least one axis must have met the test criteria. It was felt that the plate testing more accurately reproduced the flight service shock in each axis so it was not necessary to rotate the component and expose it to more events.

5.1 Component Refurbishment

A key aspect of the qualification philosophy of reusable hardware is that the SRB Project had the ability to examine, refurbish, and retest key components before they returned to service. It was hoped that as the flight rate increased in the early 1980s, the engineers would gain sufficient confidence from multiple flight exposures so they would be able to “wash, dry, and fly” the reusable hardware, thereby greatly reducing the time and cost associated with booster refurbishment and assembly. The STS-51L and STS-107 accidents eliminated that possibility. The result was that each critical component was examined after flight. In some cases, components were sent back to the manufacturer to be disassembled, rebuilt, and exposed to a series of environmental acceptance and checkout tests before being reflown.

6.0 Early Component Qualifications

In the mid-1970s, the SRB Project decided that, with the predicted flight rate and the available budget for hardware procurement, each reusable component should be qualified for a 20-mission lifetime. To get the initial set of hardware ready to fly, qualification was performed in stages: 1, 7, and then 12 missions. The two major shock events that

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required qualification testing were water impact and pyrotechnic shock. The original water impact shock was predicted to be a half-sine pulse of about 22 g peak amplitude and 150-millisecond duration. Testing on a shaker was impractical because of the high displacement so a special hydraulic fixture was developed [ref. 3]. Typical shock methods using a steel plate with a linear-shaped charge on the back were used for pyrotechnic shock testing.

7.0 Flight History

Several high frequency flight measurements were made on the first STS flights in the early 1980s, but SSP emphasis was placed on random vibration and acoustic measurements. These were ranged to capture accelerations in the 20-60 gravity root-mean-squared range and were usually saturated by the high amplitude shock events. Most of the instrumentation was located next to component installations in the forward and aft skirts (see Figure 7.0-1).

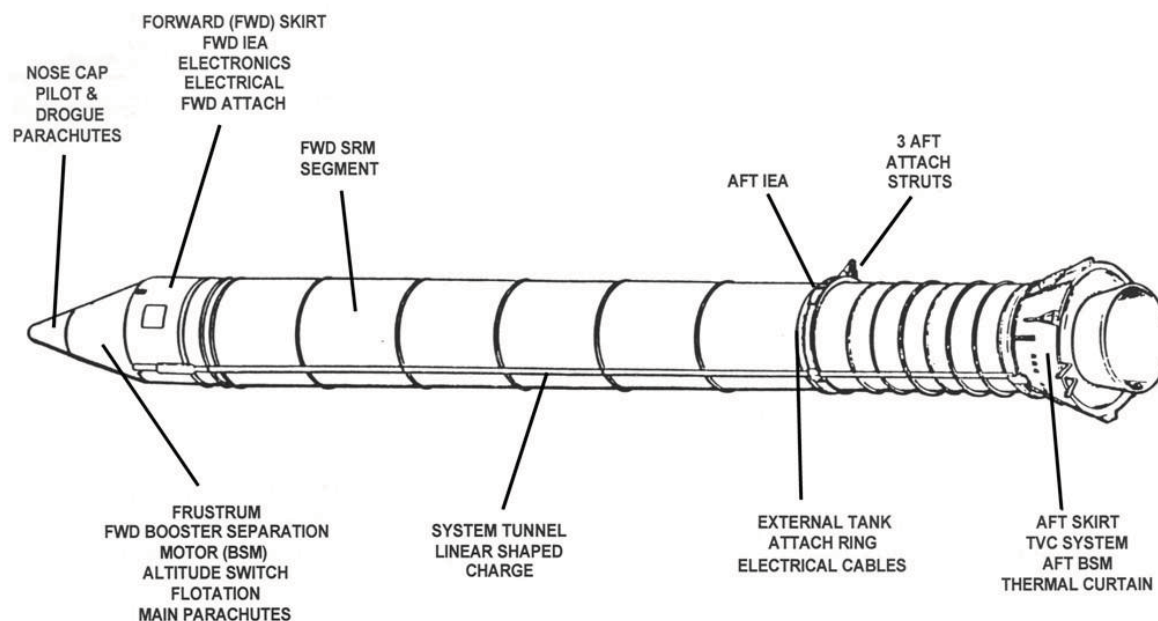


Figure 7.0-1. SRB System Components

7.1 Water Impact Damage

Instrumentation to capture shock events was added to STS-5 and STS-6 to measure the input to the forward integrated electronics assembly (IEA), located on a ring-frame in the forward skirt. As flight experience began to accumulate, several of the rate gyros located near the forward IEA experienced damage to the pivots that held the gyros in place. It appeared the pivot damage correlated with unusual water impact conditions, such as parachute failures or extreme sea conditions. A review of the vibration instrumentation

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showed that the accelerometers were clipped at water impact, which should not have happened if the acceleration levels were 22 g peak as predicted. More instrumentation was added to flights STS-41D, STS-51A, and STS-51F at the rate gyro location to investigate the pivot damage, which showed that the previous water impact criteria at that location were not adequate.

These added measurements showed that on the rigid steel motor case the original criteria were accurate. However, at the equipment locations, the local structure was responding in a more energetic manner. A third set of instrumentation was added at all component locations on STS-26, STS-27, and STS-29, which showed that similar differences in test criteria versus flight measurements were common to all locations on the secondary structures.

7.2 Test Criteria Revision and Qualification

Water impact criteria for all areas of the SRB and solid rocket motor were revised based on the measurements made subsequent to the early development flight instrumentation flights. Shock response spectra (SRS) were chosen as the best method to document the test criteria because of the relatively complex time history compared to the earlier half-sine time histories. Testing was initiated on the rate gyros to determine if water impact or pyrotechnic shocks were responsible for the pivot breakage. Early attempts to achieve the SRS levels on a shaker were unsuccessful, so a fast sine sweep was initiated in an attempt to achieve the same damage potential as the SRS. The rate gyros were tested to these criteria and the pyrotechnic shock due to frustum separation with no failures. The rate gyros were redesigned in the late 1980s using a different type of damping fluid and these gyros subsequently have not experienced pivot breakage.

SRB pyrotechnic shock criteria, in the form of shock response spectra with $Q=10$, range from 1,875 g peak (4-10 KHz) to 300,000 g peak. Components with pyrotechnic shock criteria less than 1,000 g peak were not tested to those criteria based on the 50-inch per second standard that is well documented. Water impact criteria, based on SRS, are generally 250 g peak from 70-5,000 Hz, rolling down to about 70 Gp at 20 Hz, but vary based on location [ref. 4]. The 300,000 g peak criteria are for the nozzle actuator from nozzle extension severance during SRB re-entry. A vendor that could generate those levels could not be contracted so at least one mission certification was demonstrated by severing the nozzle extension after a static motor firing. The actuators were returned to the vendor after every flight for refurbishment and retest.

8.0 Rationale for Flight after STS-51L

As the water impact criteria were being revised based on the flight measurements, the SRB Project began to evaluate the impact to the component qualification and flightworthiness. Attempts were made to test the range safety battery and the IEA components, which experienced structural failures during testing. The batteries have a plastic composite case with mounting feet, which sheared during the attempted test and the IEA, which weighs over 200 pounds, and cracked its mounting lugs during the testing. Neither had experienced such failures during flight.

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The SSP and the SRB Project decided that qualification for existing SRB hardware could be done by analysis using the following rationale:

- Existing SRB hardware withstood actual water impacts without damage.
 - Water impact shock is an overstress environment rather than fatigue, so if hardware survives initial impact it will likely survive at least 19 more cycles.
 - There have been no failures attributed to normal (i.e., 75 feet per second) water landing.
- SRB components have been exposed to water impacts approximately 46 percent higher than normal due to parachute failures.
 - Only component damage was due to cavity collapse water geyser effects on aft IEA.
- All components exposed to random vibration and pyrotechnic shock were qualified for those environments and demonstrated adequate design margins during the qualification test program.
 - Pyrotechnic shock is more severe in high frequencies where most shock failures occur.
- All critical components are subjected to post flight assessment where potential water impact damage will be discovered.
 - Acceptance testing consists of random vibration and thermal tests.

The last point was particularly important because most components had completed their function before water impact occurred so failures after that could be corrected before the next use.

9.0 Flight History from STS-26 to End of Program

Shock measurements made on STS-26, STS-27, and STS-29 verified the preliminary criteria based on the earlier measurements. No hardware failures have been attributed to shock or random vibration, even though there have been flights (i.e., parachute failure) where the test criteria were exceeded. The qualification test methods that are used have enough inherent conservatism in them to be sufficient to qualify the designs, rendering arbitrary test margins unnecessary.

The aft IEA, which is attached to the aft ET attach ring with a fiberglass enclosure, is occasionally damaged due to the water geyser effect. When the SRBs hit the water they displace the water, which rushes back in and runs up the side of the case on the lee side. If the box is on the side where the cavity collapses, it can be knocked off its mounting by the force of the water. Figure 9.0-1 is a measurement at that location showing the initial impact and the cavity collapse event about a second later. Rubber snubbers were added between the IEA and the fiberglass enclosure to mitigate this effect.

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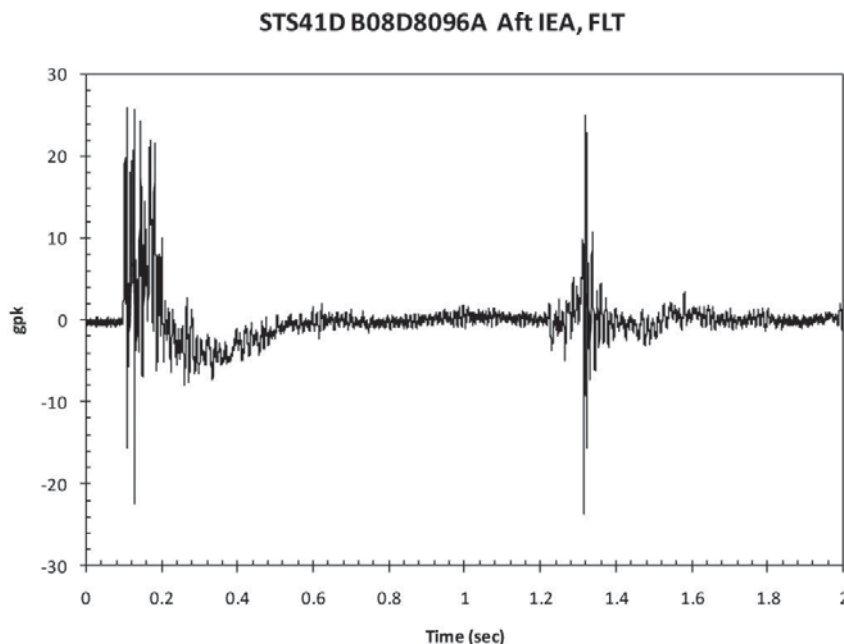


Figure 9.0-1. Water Impact Shock Measurement at the ET Attach Ring Location Showing Cavity Collapse. Accelerometer was oriented in the Flight Direction.

Hardware designed and qualified after STS-51L return to flight was successfully tested for water impact for up to 20 missions using the new shock criteria. The units were tested on vibration shakers using the SRS software. The first attempts often under tested in the 70-100 Hz region where displacements were high and in the 2-5 KHz region. The MSFC purchased larger shakers and subsequent attempts have been more successful. Comparisons of the time histories produced by the shakers and flight measurements do not show much similarity so some effort will be expended in the future to try to match the time histories [ref. 5].

10.0 Experience Summary and Conclusions

The SRB Project has successfully flown and reused hardware up to 17 missions after qualifying the hardware to shock criteria based on maximum expected flight environments. Refurbishment and acceptance testing on the recovered hardware before reuse was a key element in the acceptance of the qualification philosophy. After flight measurements showed that the time histories were exceeded, early water impact qualification test criteria, based on half-sine time histories, were replaced with shock response spectra. Early attempts to qualify hardware to the new criteria were not successful until sufficient experience was gained in generating the SRS and new shaker hardware was purchased. Testing large components to these water impact criteria will present a challenge and more work must be done to demonstrate this capability.

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11.0 Acronyms List

ATK	Alliant Techsystems Inc.
dB	Decibel
DCI	Dynamic Concepts Incorporated
ET	External Tank
g	Gravity
GSFC	Goddard Space Flight Center
IEA	Integrated Electronics Assembly
JPL	Jet Propulsion Laboratory
JSC	Johnson Space Flight Center
KSC	Kennedy Space Center
LaRC	Langley Research Center
MIL-STD	Military Standard
MSFC	Marshall Space Flight Center
MTSO	Management and Technical Support Office
NESC	NASA Engineering and Safety Center
SRB	Solid Rocket Booster
SRS	Shock Response Spectra
SSP	Space Shuttle Program
STS	Space Transportation System

12.0 References

1. Madden, R., Wright, H. A., and Kross, D. A. "Scaling of Water Impact Data for Space Shuttle Solid Rocket Booster," The Shock and Vibration Bulletin, Vol. 46, September 1976.
2. Kacena, W., McGrath, M. B., Rader, W. P. "Aerospace Systems Pyrotechnic Shock Data (Ground Test and Flight)," Final Report Contract No. NAS5-15208, March 1970.
3. Seco-Dyn Inc., "Water Impact Shock Test System," Final Report Contract No. NAS8-31945, November 1977.
4. Anonymous. "SRB Vibration, Acoustic and Shock Design & Test Criteria," NASA MSFC Document SE-019-049-2H.
5. Ferebee, R., Clayton, J., Alldredge, D., and Irvine, T. "An Alternative Method of Specifying Shock Test Criteria," NASA/TM-2008-215253, April 2008.

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